(4)

Final Technical Report

DYNAMICS OF OCEANIC MOTIONS

ONR Contract N00014-75-C-0225

1 January, 1975 — 29 February, 1984

by
Allan R. Robinson
Principal Investigator
26 December, 1990

This project researched the dynamics of oceanic motions: aspects of the theory and modeling of fundamental dynamical and energetic processes in the sea and their interactions, and the relationship of theory and modeling to the interpretation, analysis and design of observational data and experiments. Research was directed towards the dynamics and the forecasting of the low frequency variability of ocean currents (mid-ocean eddies and intense current systems), the mid-latitude general circulation, and surface boundary and internal wave layer interactions. Our modeling research was directed toward studies of the local dynamics of open regions of the ocean (i.e., arbitrary regions with flow across their boundaries), and the relationship of such regional dynamics to the larger scale general circulation in which it is embedded. The approach was adopted as appropriate for application to intensive local data sets and for the development and testing of forecast methods for oceanic synoptic/mesoscale motions. This report consists primarily of a listing of the Produced Under This Project.

The project produced 48 refereed publications and 22 additional technical reports which are indexed on attached lists. The research summary will reference the publications since the reports are preliminary or extended versions of the publications except for report # 13 which was the Brunn Memorial Lecture I delivered to the General Assembly of the Intergovernmental Oceanographic Commission and Report # 19 which is the Proceedings of the first Ocean Prediction Workshop (OPW81) at the Naval Postgraduate School which I cochaired and edited.

Highlight contributions include a book on mesoscale eddies (Publication # 36), a pioneering primitive equation EGCM simulation (8), the development and calibration of the Harvard open ocean model (25, 35), the definition of fine mesoscale structure in the California Current System (42), the first real time mesoscale dynamical forecast (43) and the introduction of the Ocean Predictive Descriptive System concept (45). Eight review and overview articles and chapters dealt with the mesoscale (3), modeling for forecasting (13), ocean and climate models (22), eddies and circulation (23), eddy dispersion (34), the results of the MODE and POLYMODE programs (17, 32), and large oceanographic programs (26). There were six Ph.D. theses published (1, 2, 12, 27, 47, 48).

o Dup

HARVARD UNIVERSITY

DIVISION OF APPLIED SCIENCES

PIERCE HALL
CAMBRIDGE, MASSACHUSETTS 02138
(617)-495-2819

ALLAN R. ROBINSON
Gordon McKay Professor
of Geophysical Fluid Dynamics

January 2, 1991

Mr. Robert H. Tanner
Department of the Navy
Office of Naval Research
Resident Representative
The Charles Stark Draper Laboratory
555 Technology Square
Cambridge, MA 02139

Dear Mr. Tanner,

Enclosed please find our final technical report for ONR Contract Number N00014-75-C-0225 "Dynamics of Oceanic Motions" which terminated February 1984.

Yours sincerely,

Allan R. Robinson
Principal Investigator

ARR:m

enclosure: (1) copy Final Technical Report

cc: (1) Ms. M. Sterns/Harvard - OSR
(1) Ms. R. Demone/Harvard - DAS/accounting
(3) Dr. D. Evans/ONR
(1) Director/NRL
(4) Defense Technical Information Center

Model developments included the horizontal (4) and vertical (44) codes of the HOOM, nonlinear modal analysis (14) and importantly the Harvard objective analysis (46). Data analyses synthesized the MODE-1 data base (5), calibrated the XBT as a scientific instrument (10), and produced large scale maps of mesoscale features from the GEOS-3 altimeter (37). Fundamental theoretical studies were carried out relating to stable and unstable planetary waves (6, 21), and Gulf-Stream meanders and rings (41, 11). The theoretical basis for general energetic study of open regions was established (16), and a parameterization of eddy diffusion hypothesized (15). Studies of the generation and forcing of mesoscale eddies invoked momentum and buoyancy flux (18, 19, 30) and pressure radiation (20) mechanisms. Boundary dynamical studies included the seasonal cycle of the surface boundary layer and its interaction with a deep baroclinic Rosby wave field (24, 38) and wind forced coastal currents (39) and upwelling (40). Topics at higher frequency included substantial studies of internal wave dynamics and interactions (28, 29), the dynamics of long-period tides (33), and the generation of microstructure via a double-diffusive mechanism (9).

Publications:

1. Calman, J. (1975), Experiments on Instability of Rotating Stratified Fluid of High Schmidt Number, Harvard University, Ph.D. Thesis.

2. Flierl, G. R. (1975), Gulf Stream Meandering, Ring Formation and Ring Propagation, Harvard Univerity, Ph.D. Thesis.

3. Robinson, A. R. (1975), The Variability of Ocean Currents, *Reviews of Geophysics and Space Physics* 13, 598–601.

4. Hirsh, J. E. and W. L. Briggs (1976), Sparse Matrix Problems in a Finite Element Open Ocean Model, *Space Matrix Computations*, Academic Press.

5. McWilliams, J. C. and G. R. Flierl (1976), Optimal Quasigeostrophic Wave Analysis of the MODE Array Data, *Deap Sea Research* 23, 285–300.

6. McWilliams, J. C. (1976), Large Scale Inhomogeneity and Mesoscale Ocean Waves: A Single Stable Wave Field, *Journal of Marine Research* 34, 423–456.

7. Robinson, A. R. (1976), Eddies and Ocean Circulation," *Oceanus*, Spring 1976, 2–17.

8. Robinson, A. R., D. E. Harrison, Y. Mintz, and A. J. Semtner (1976), Eddies and the General Circulation of an Idealized Oceanic Gyre: A Wind and Thermally Driven Primitive Equation Numerical Experiment, *Journal of Physical Oceanography* 7, 182–207.

9. Calman, J. (1977), Experiments on High Richardson Number Instability of a Rotating, Stratified Shear Flow, *Dynamics of Atmospheres and Oceans* 1, 277–298.

10. Flierl, G. R. and A. R. Robinson (1977), XBT Measurements of Thermal Gradients in the MODE Eddy, *Journal of Physical Oceanography* 7(2), 300–302.

11. Flierl, G. R. (1977), Applications of Linear Quasi-Geostrophic Dynamics to Gulf Stream Rings, *Journal of Physical Oceanography* 7, 365–379.

12. Harrison, D. E. (1977), On Mesoscale-Mean Field Interaction in the Ocean, Harvard University, Ph.D. Thesis.

13. Robinson, A. R. (1977), Numerical Modeling and Global Ocean Forecasting, in *Science, Technology and the Modern Navy.*

14. Flierl, G. R. (1978), Models of Vertical Structure and the Calibration of Two-Layer Models, *Dynamics of Atmospheres and Oceans* 2, 341–382.

15. Harrison, D. E. (1978), On the Diffusion Parameterization of Mesoscale Eddy Effects from a Numerical Ocean Experiment, *Journal of Physical Oceanography* 8, 913–918.

16. Harrison, D. E. and A. R. Robinson (1978), Energy Analysis of Open Regions of Turbulent Flows — Mean Eddy Energetics of a Numerical Ocean Circulation Experiment, *Dynamics of Atmospheres and Oceans* 2, 185–211.

17. MODE Group (including Harrison, Muller and Robinson) (1978), The Mid-Ocean Dynamics Experiment, *Deep-Sea Research* 25, 859–910.

18. Frankignoul, C. and P. Muller (1979), On the Generation of Geostrophic Eddies by Surface Buoyancy Flux Anomalies, *Journal of Physical Oceanography* 9, 1209–1213.

19. Harrison, D. E. (1979), On the Equilibrium Response to Fluctuating Winds and Mesoscale Motions in the Ocean, *Journal of Geophysical Research* 84, 1221–1224.

20. Harrison, D. E. and A. R. Robinson (1979), Boundary Forced Planetary Waves: A Simple Model Mid-Ocean Response to Strong Current Variability, *Journal of Physical Oceanography* 9(5), 919–929.

21. Radach, G. (1979), On the Effects of Vertical Eady Viscosity on Eddy and Rossby Waves, *Dynamics of Atmospheres and Oceans* 4(1), 121–144.

22. Robinson, A. R. (Editor) (1979), *Ocean Models and Climate Models*: Proceedings of the GARP/SCOR Helsinki Conference, *Dynamics of Atmospheres and Oceans* 3(2–4).

23. Robinson, A. R., D. E. Harrison and D. B. Haidvogel (1979) Mesoscale Eddies and General Ocean Circulation, *Dynamics of Atmospheres and Oceans* 3(2–4), 143–180.

24. Stevenson, J. W. (1979), On the Effect of Dissipation on Seasonal Thermocline Models, *Journal of Physical Oceanography* 9, 57–64.

25. Haidvogel, D. B., A. R. Robinson and E. Schulman (1980), The Accuracy, Efficiency and Stability of Three Numerical Models with Application to Open Ocean Problems, *Journal of Computational Physics* 34(1), 1–53.

26. Robinson, A. R. and W. Simmons (1980), A New Dimension in Physical Oceanography, *Oceanus* 23(1), 40–52.

27. Stevenson, J. W. (1980), Response of the Surface Mixed Layer to Quasi-Geostrophic Oceanic Motions, Harvard Univeristy, Ph.D Thesis.

28. McComas, C. H. and P. Muller (1981), Time Scales of Resonant Interactions among Oceanic Internal Waves, *Journal of Physical Oceanography* 11, 139–147.

29. McComas, C. H. and P. Muller (1981), The Dynamic Balance of Internal Waves, *Journal of Physical Oceanography* 11, 970–987.

30. Muller, P. and C. Frankignoul (1981), Direct Atmospheric Forcing of Geostrophic Eddies, *Journal of Physical Oceanography* 11, 287–308.

31. Robinson, A. R. and D. B. Haidvogel (1981), Dynamical Forecast Experiments with a Barotropic Open Ocean Model, *Journal of Physical Oceanography* 10(12), 1909–1928.

32. Robinson, A. R. (1982), Dynamics of Ocean Currents and Circulation: Results of POLYMODE and Related Investigation in *Topics in Ocean Physics*, Proc. Summer Sch. 1980, (A. Osbourne and P. M. Rizzoli, eds.), Soc. Italiana di Fisica, Bologna, Elsevier, NY.

33. Carton, J. A. (1983), The Variation with Frequency of the Long-Period Tides, *Journal of Geophysical Research* 8, 7563–7572.

34. Haidvogel, D. B., C. Rooth and A. R. Robinson (1983), Eddy-Induced Dispersion and Mixing, in *Eddies in Marine Science* (A. R. Robinson, ed.), Springer-Verlag, New York/Heidelberg, 481–489.

35. Miller, R. N., A. R. Robinson and D. B. Haidvogel (1983), A Baroclinic Quasi-Geostrophic Open Ocean Model, *Journal of Computational Physics* 50(1), 38–70.

36. Robinson, A. R. (1983), Introduction, *Eddies in Marine Science* (A. R. Robinson, ed.), Springer-Verlag, New York/Heidelberg.

37. Robinson, A. R., N. E. Huang, D. D. Leitao and C. G. Parra (1983) A Study on the Variability of Ocean Currents in the Northwestern Atlantic Using Satellite Altimetry, *Journal of Physical Oceanography* 13(4), 565–585.

38. Stevenson, J. W. (1983), The Seasonal Variation of the Surface Mixed Layer Response to the Vertical Motions of Linear Rossby Waves, *Journal of Physical Oceanography* 13(7), 1225–1268.

39. Carton, J. A. (1984), Response of the Coastal Ocean to an Isolated Storm, *Journal of Physical Oceanography* 14, 114–124.

40. Carton, J. A. and S. G. H. Philander (1984), Coastal Upwelling Viewed as a Stochastic Phenomenon, *Journal of Physical Oceanography* 14, 1499–1509.

41. Flierl, G. R. and A. R. Robinson (1984), On the Time-Dependent Meandering of a Thin Jet, *Journal of Physical Oceanography* 14(2), 412–423.

42. Mooers, C. N. K. and A. R. Robinson (1984), Turbulent Jets and Eddies in the California Current and Cross-Shore Transports, *Science*, 52–54.

43. Robinson, A. R., J. A. Carton, C. N. K. Mooers, L. J. Walstad, E. F. Carter, M. M. Rienecker, J. A. Smith and W. G. Leslie (1984), A Real Time Dynamical Forecast of Ocean Synoptic/Mesoscale Eddies, *Nature* 309(5971), 781–783.

44. Robinson, A. R. and R. N. Miller (1984), Dynamical Forecast Experiments with a Baroclinic Open Ocean Model, in *Proceedings of Conference on Predictability of Fluid Motions* (G. Holloway and B. West, eds.), American Institute of Physics, Proceedings No. 106, AIP, New York.

45. Robinson, A. R. and W. G. Leslie (1985), Estimation and Prediction of Oceanic Fields, *Progress in Oceanography* 14, 485–510.

46. Carter, E. F. and A. R. Robinson (1987), An Analysis Model for the Estimation of Oceanic Fields, *Journal of Atmosphere and Oceanic Technology* 4, 49–74.

47. Tu, K. (1981), A Combined Statistical and Dynamical Approach to Regional Forecast Modeling of Open Ocean Currents, Harvard Univeristy, Ph.D Thesis.

48. Carter, E. F. (1983), The Statistics and Dynamics of Ocean Eddies, Harvard Univeristy, Ph.D Thesis.

Reports:

1. McWilliams, J. C. and A. R. Robinson (1974), Equatorial Shear Measurements, *Reports in Meteorology and Oceanography* 8, Harvard University.

2. Flierl, G. R. (1975), Quasi-Eulerian Quantities Derived from Float Measurements and True Eulerian Quantities, MODE Hot Line News 85.

3. Flierl, G. R., V. Kamenkovich and A. R. Robinson (1975), Gulf Stream Meandering and Gulf Stream Ring Eddy Production Mechanisms, *Dynamics and the Analysis of MODE I*, 136–137.

4. Harrison, D. E. (1975), Forcing by Fluctuating Winds, *Dynamics and the Analysis of MODE I*, 136–137.

5. Hendershott, M. (with a contribution by J. Hirsh) (1975), Quasigeostrophic Prediction, *Dynamics and the Analysis of MODE I*, 86–93.

6. Hirsh, J. E. and W. L. Briggs (1975), Sparse Matrix Problems in a Finite Element Open Ocean Model, TR-23-75 Division of Engineering and Applied Physics, Harvard University.

7. Holland, W. R. and A. R. Robinson (1975), Numerical Simulation Models, *Dynamics and the Analysis of MODE I*, 170.

8. McWilliams, J. C. (1975), Baroclinic Instability and the MODE Observations, *Dynamics and the Analysis of MODE I*, 94–112.

9. McWilliams, J. C. and G. R. Flierl (1975), Quasigeostrophic Wave Analyses, *Dynamics and the Analysis of MODE I*, 61–85.

10. Robinson, A. R. (1975), Summary of Theoretical and Numerical Modelling of Low-Frequency Mesoscale Processes, *MODE Hot Line News* 81.

11. Robinson, A. R., Y. Mintz, R. Haney, Y.-J. Han, D. E. Harrison and K. Takano (1975), Mesoscale Eddies and the General Circulation of Numerical Model Gyres, *Dynamics and the Analysis of MODE I*, 182–188.

12. Contributions to "Balance of Terms and Integral Balances," and "Topographic Dynamics: A. The Results of MODE-I and Topographic Influences" (1975), *Dynamics and the Analysis of MODE I*, 27–60 and 189–250.

13. Robinson, A. R. (1976), Dynamics of the Kuroshio Current: Bruun Memorial Lecture, Intergovernmental Oceanographic Commission (UNESCO), Technical Series.

14. Harrison, D. E. and A. R. Robinson (1977), Eddy Kinetic Energy Analysis Over Open Regions of a Model Ocean, *POLYMODE News*.

15. Robinson, A. R. (1977), *Proceedings of the JOC/SCOR Joint Study Conference on General Circulation Models of the Ocean and Their Relations to Climate* (Helsinki, May, 1977).

16. Robinson, A. R. (1977), Results of MODE and Succeeding Explorations. Theory and Modeling of Ocean Eddies: Contribution of the U.S. Delegation to the Yalta POLYMODE Theoretical Institute, U.S.P.M.O.C. (P. Rhines, Editor, Dept. of *Meteorology*, M.I.T., Cambridge, Mass. 02139.

17. Haidvogel, D. B., E. E. Schulman and A. R. Robinson (1978), The Accuracy, Efficiency and Stability of Three Numerical Models with Application to Open Ocean Problems, *Reports in Meteorology and Oceanography II*, Harvard University, Cambridge, MA.

18. Miller, R. N., A. R. Robinson and D. B. Haidvogel (1981), A Baroclinic Quasi-Geostrophic Open Ocean Model, *Reports in Meteorology and Oceanography* 16, A Harvard Open Ocean Model Report, Harvard University, Cambridge, MA.

19. Mooers, C. N. K, S. A. Piascek and A. R. Robinson (1981) Ocean Prediction: The Scientific Basis and the Navy's Needs, A Status and Prospectus Report, Proceedings of the Ocean Prediction Workshop, Monterey, California, May 1981.

20. Bogden, P. S. (1983), The Mesoscale Temperature Variability in the Western North Atlantic, *Reports in Meteorology and Oceanography 19*, Honors BA Thesis.

21. Carter, E. F. (1983), The Statistics and Dynamics of Ocean Eddies, *Reports in Meteorology and Oceanography* 18, Harvard University, Ph.D. Thesis.

22. Robinson, A. R. (1983), Description and Prediction of Oceanic Fields: Data Assimilation and Optimal Estimation, Proceedings of the Study Conference on Large-Scale Oceanographic Experiments in the World Climate Research Programme, CCO/SCOR-JSC/WCRP, Tokyo.